A FRAMEWORK TO DETERMINE NEW SYSTEM REQUIREMENTS UNDER DESIGN PARAMETER AND DEMAND UNCERTAINTIES

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Overview

- Use an optimization-based approach to identify design requirements of new systems
  - Address issue that new systems operate along with existing systems
  - Seek fleet-level performance and capabilities
- Development of a decision-support framework
  - Determine requirements for – and suggest design of – a new system that will optimize fleet-level objectives to support acquisition
  - Fleet-level objectives are functions of new system requirements
  - Account for design parameter and demand uncertainties
- Used the framework to generate tradeoffs between fleet-level productivity and cost
  - Motivated by energy and fuel consumption, reflected via operating cost
  - Route network extracted from Air Mobility Command (AMC) operations
  - New aircraft design change across range of best tradeoff solutions

INTRODUCTION AND MOTIVATION

Motivation

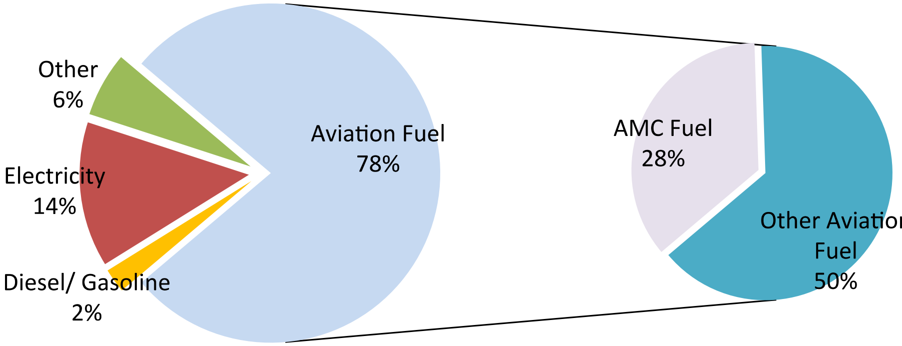
- Fleet-level energy efficiency poses significant risks and operational constraints on military operational flexibility[1]
- Growing emphasis on reducing fuel usage in military systems
  - Streamline operations of existing fleet
  - Acquire efficient platforms and platforms that lead to fleet-level efficiency
- Lack of a framework that captures the effect that fuel-saving measures can have on fleet-level performance metrics[2]
  - Do not accurately explore tradeoff opportunities
- Determining design requirements of 'yet-to-be-designed' systems to improve fleet-level metrics is difficult
  - Couples operation decisions with new system design
  - Non-deterministic nature of fleet operations
  - Assumptions in deterministic models leads to sub-optimal performance

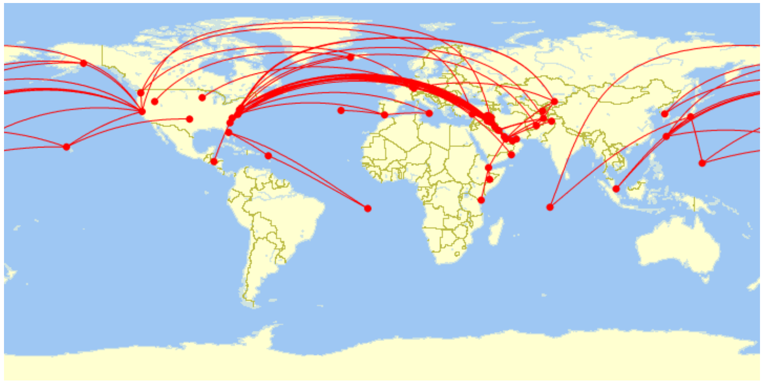
[1]*AMC Vice Commander: Saving fuel secures the future – one gallon at a time. Inside AMC*

[2]*DoD Acquisition and Technology: Energy Efficiency starts with the acquisition process*

Air Mobility Command

- AMC: One of the major command centers of the U.S. Air Force
- AMC is the DoD's single largest aviation fuel consumer (28 % of total aviation fuel use)*.
- Non-deterministic nature of AMC operations
  - Demand is highly asymmetric
  - Demand fluctuation on a day to day basis
  - Routes flown vary based on demand
  - Limited aircraft types: C-5, C-17, C-130, Boeing 747-F, KC-135, etc.
- AMC's mission profile includes
  - Worldwide cargo and passenger transport**
  - Aerial refueling and aeromedical evacuations
- Used Global Air Transportation Execution System (GATES) dataset
  - Large route network (1804 routes)





Sample route network from GATES

Aviation fuel savings: AMC leading the charge. Air Mobility Command
**This work only addresses cargo transport*

SCOPE AND METHOD OF APPROACH

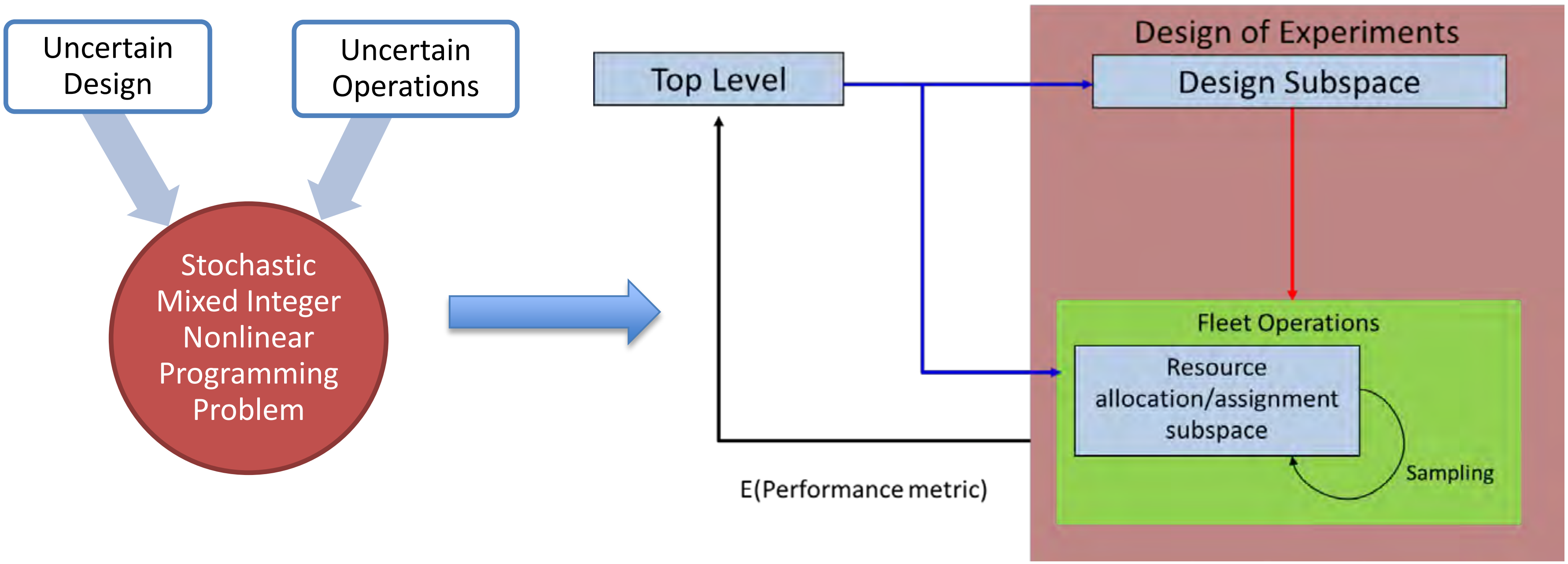
How can our approach help?

- Our methodology
  - Helps determine the requirements for – and describe the design of – a new aircraft for use in the AMC fleet
  - Optimize fleet-level metrics that address performance and fuel use
- Describe how design requirements of the new aircraft would change for different tradeoff opportunities between productivity and cost

Method of Approach (1)

- Consider this as an optimization problem
  - Objectives
    - Fleet Productivity (speed of payload delivery)
    - Fleet Direct Operating Cost (strongly driven by fuel use)
  - Variables
    - New aircraft requirements (pallet capacity, range, speed)
    - New aircraft design variables (AR, W/S , T/W)
    - Assignment variables (flight on a particular route)
  - Constraints
    - Cargo demand
    - Aircraft performance (takeoff distance)
    - Fleet Operations (maximum operational hours)

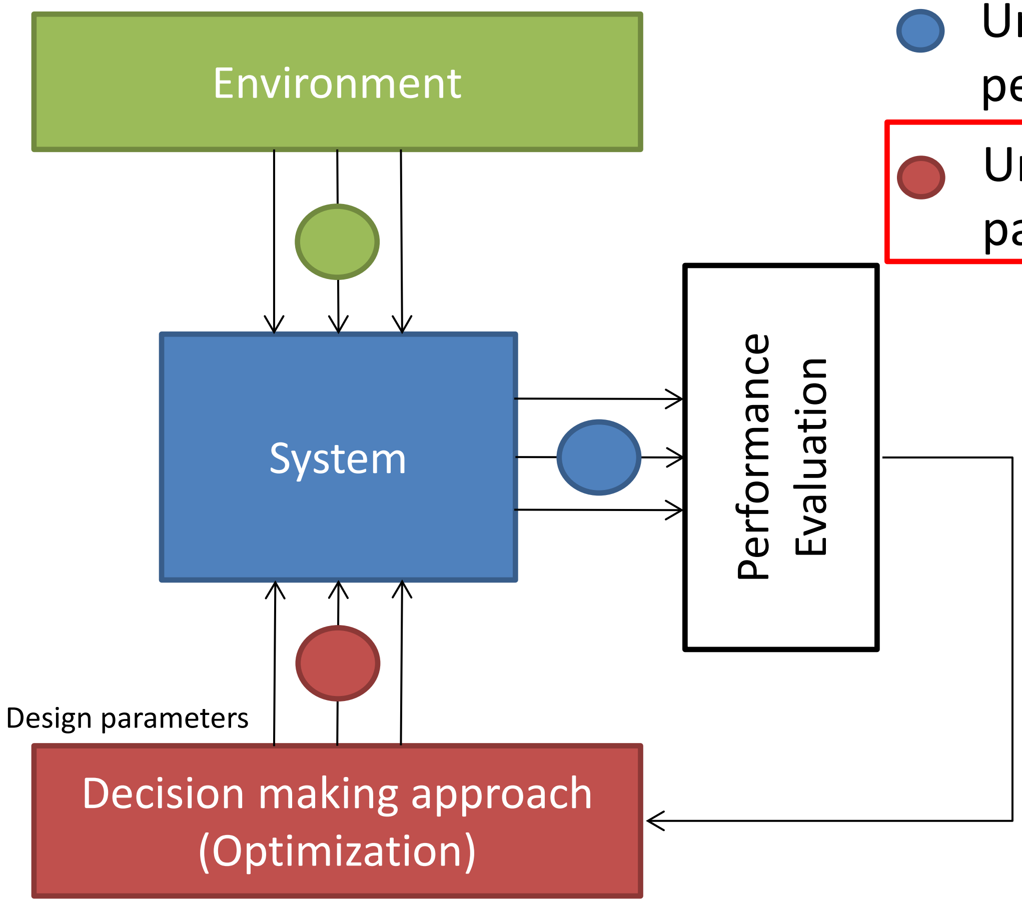
Method of Approach (2)



Monolithic Formulation

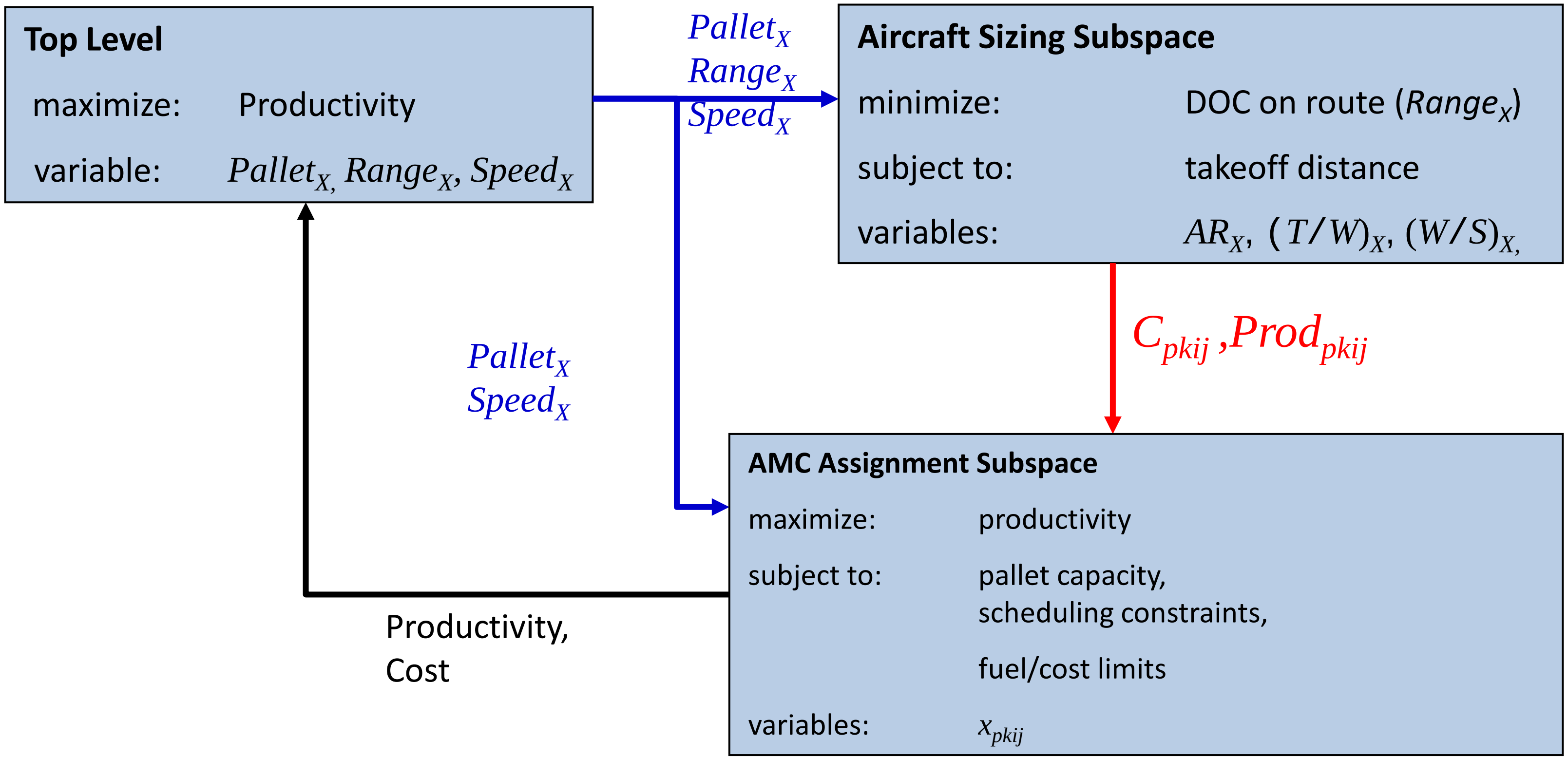
Subspace Decomposition

Classes of Uncertainties

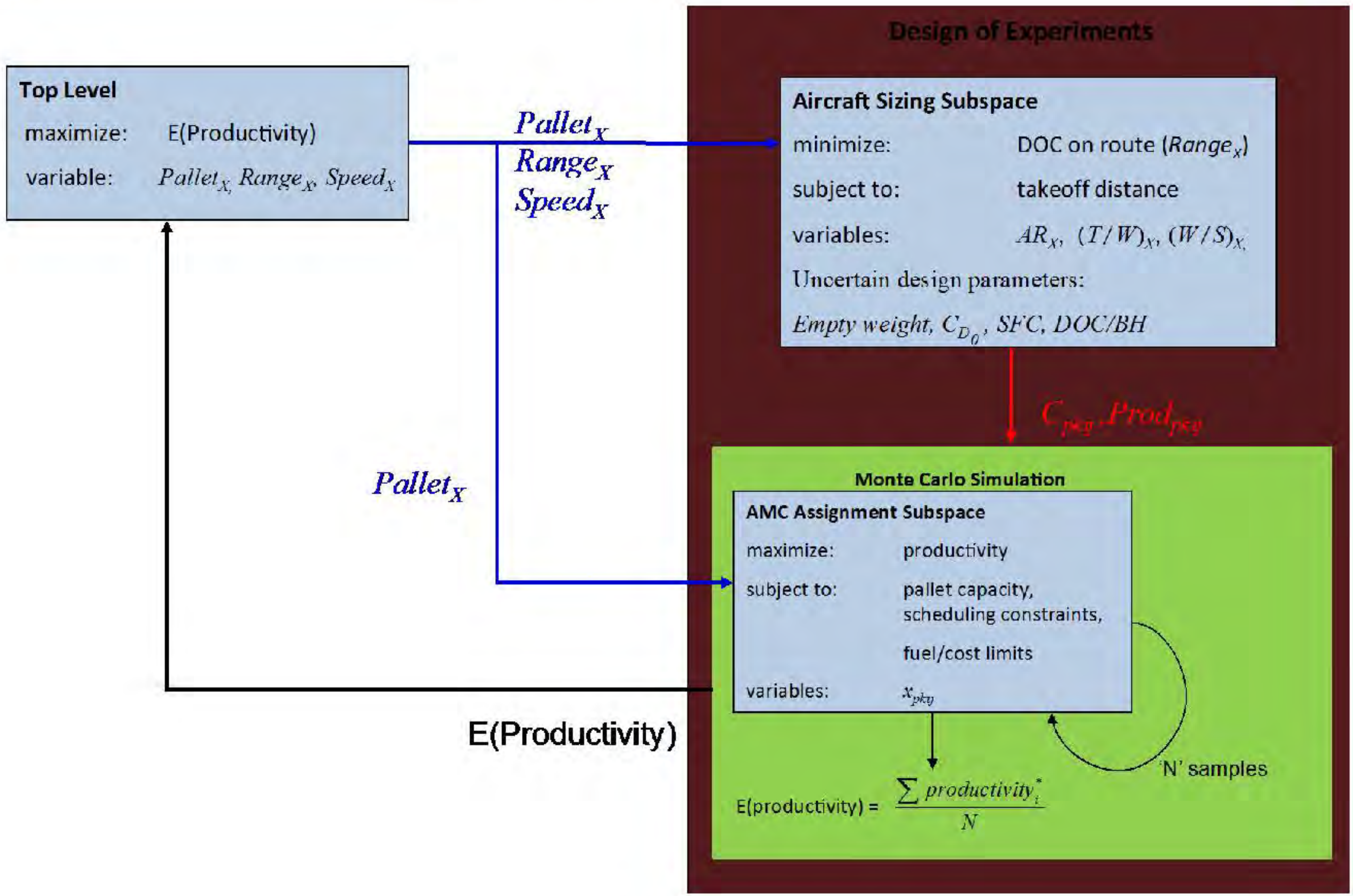


- Uncertainty in operations
- Uncertainty in observed system performance
- Uncertainty in design parameters

Subspace Decomposition Approach (Deterministic)



Subspace Decomposition Approach



Top Level Subspace

Maximize	Fleet-level Productivity	Productivity = Speed x Capacity
Subject to	$14 \leq Pallet_X \leq 38$	Pallet Capacity Bounds
	$350 \leq Speed_X \leq 550$	Cruise speed bounds (knots)
	$2400 \leq Range_X \leq 3800$	Range at maximum payload bounds (nm)
	$Speed_X\,,\; Range_X \in R^+$ $Pallet_X \in Z^+$	Design variables

- Pallet capacity, Range and Speed bounds are set by strategic air lift aircraft description

Aircraft Sizing Subspace

Minimize	$(DOC_{Pallet,Range,Speed})_X$	Direct Operating Cost
Subject to	$6.0 \le (AR)_X \le 9.5$	Wing aspect ratio bounds
	$65 \le (W/S)_X \le 161$	Wing loading bounds (lb/ft^2)
	$0.18 \le (T/W)_X \le 0.35$	Thrust-to-weight ratio bounds
	$S_{TO}\left(Pallet_X, (AR)_X, (W/S)_X, (T/W)_X\right) \le D_{takeoff}$	Aircraft takeoff distance
	$(AR)_X, (W/S)_X, (T/W)_X \in R^+$	Design variables

- Bounds for aircraft design variables based on current military cargo aircraft

Uncertainty in Aircraft Design Parameters

Uncertain design parameter	Range of values
ΔW_E (lbs) – empty weight	±10%
ΔC_{D_0} – drag coefficient	±10%
ΔDOC/BH ($/hr) – direct operating cost / block hour	±10%
ΔSFC (1/hr) – specific fuel consumption	±10% (Baseline value: 0.5)

- Four-factor, three-level full factorial design of experiments (DOE)
  - Levels: 90%, 100% ,and 110% of baseline or empirically-predicted value
  - 81 experiments = 81 sizing + allocation under uncertainty
- Best aircraft design based on mean from DOE trials
  - Our approach to account for uncertainty with low computational cost

Fleet Assignment Subspace

Maximize

$$\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j}\cdot\left(Speed_{p,k,i,j}\cdot Pallet_{p,k,i,j}\right)$$

Productivity = Speed × Capacity

Subject to

$$\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j}\cdot C_{p,k,i,j}\leq M$$

Fleet-level DOC limits

$$\sum_{i=1}^{N} x_{p,k,i,j}\geq\sum_{i=1}^{N} x_{p,k+1,i,j}\quad\forall k=1,2,3\ldots K,$$

$$\forall p=1,2,3\ldots P,\quad\forall j=1,2,3\ldots N$$

Node balance constraints

Fleet Assignment Subspace

Subject to

$$\sum_{p=1}^{P}\sum_{k=1}^{K} Cap_{p,k,i,j} \cdot x_{p,k,i,j} \geq dem_{i,j}$$

$$\forall i = 1, 2, 3 \ldots N, \forall j = 1, 2, 3 \ldots N$$

Demand constraints

$$\sum_{i=1}^{N} x_{p,1,i,j} \leq O_{p,i} \quad \forall p = 1,2,3 \ldots P, \forall i = 1,2,3 \ldots N$$

Starting location of aircraft constraints

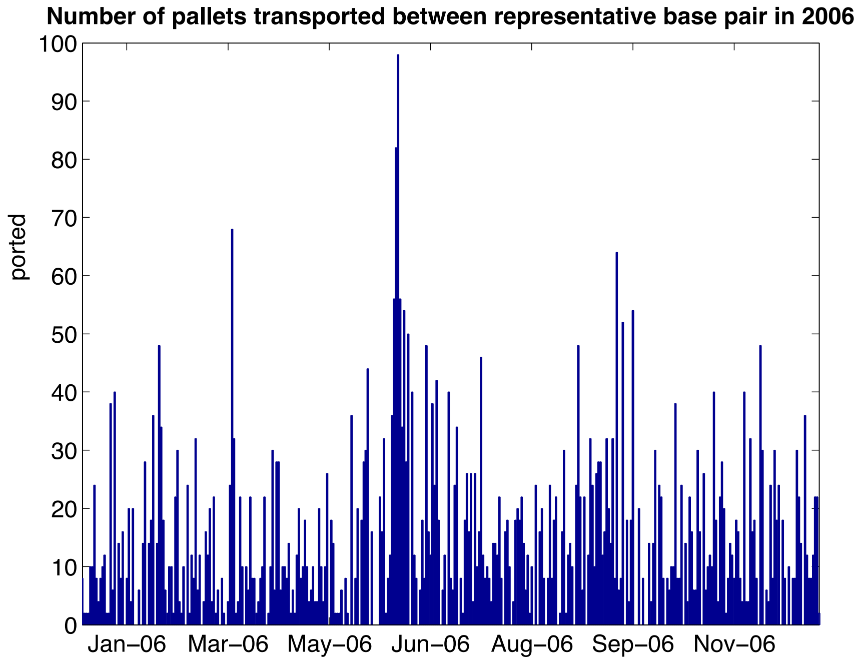
$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j} \cdot BH_{p,k,i,j} \leq B_P \quad \forall p = 1, 2, 3 \ldots P$$

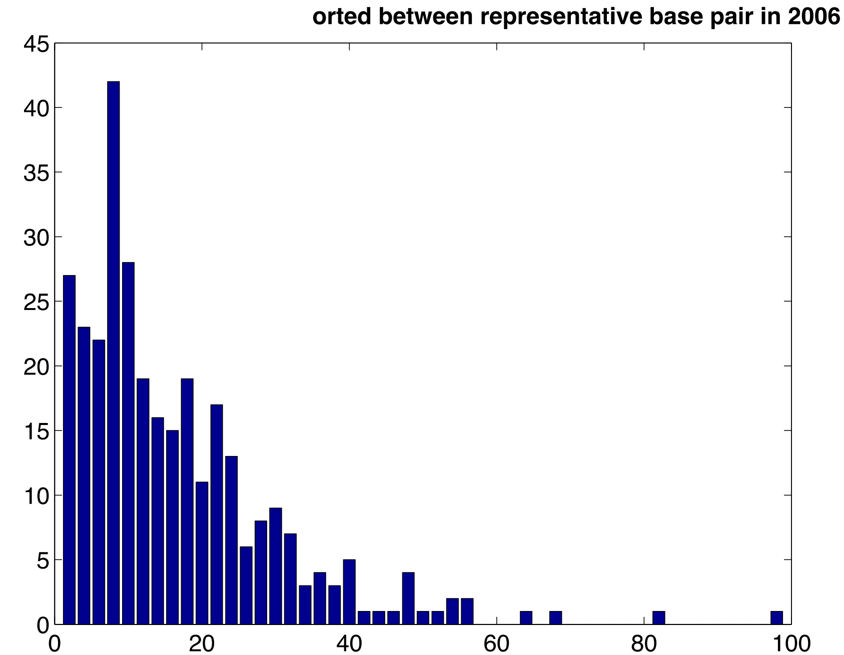
Trip constraints

$$x_{p,k,i,j} \in \{0,1\}$$

Binary decision variable

Uncertainty in Pallet Cargo Demand





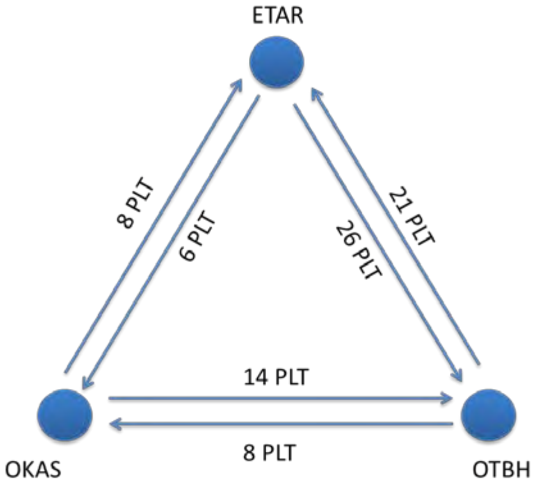
- Highly uncertain cargo demand
- Monte Carlo sampling (MCS) methods
  - Repeated deterministic calculations for statistical distribution of input random parameters

Palletized and Oversized Cargo Transport for Military Airlift Operations

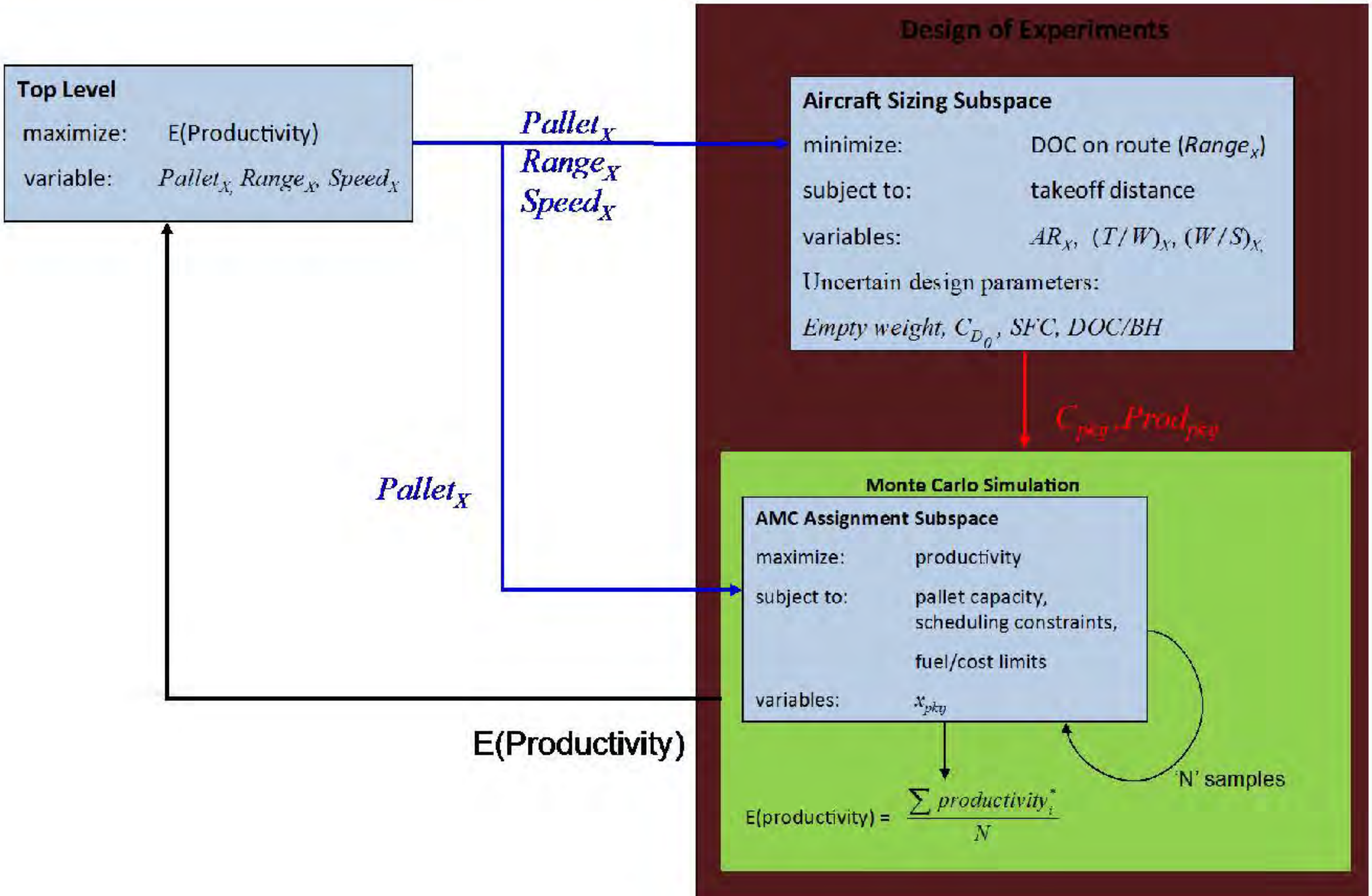
SCENARIOS & STUDIES

Three-base Problem

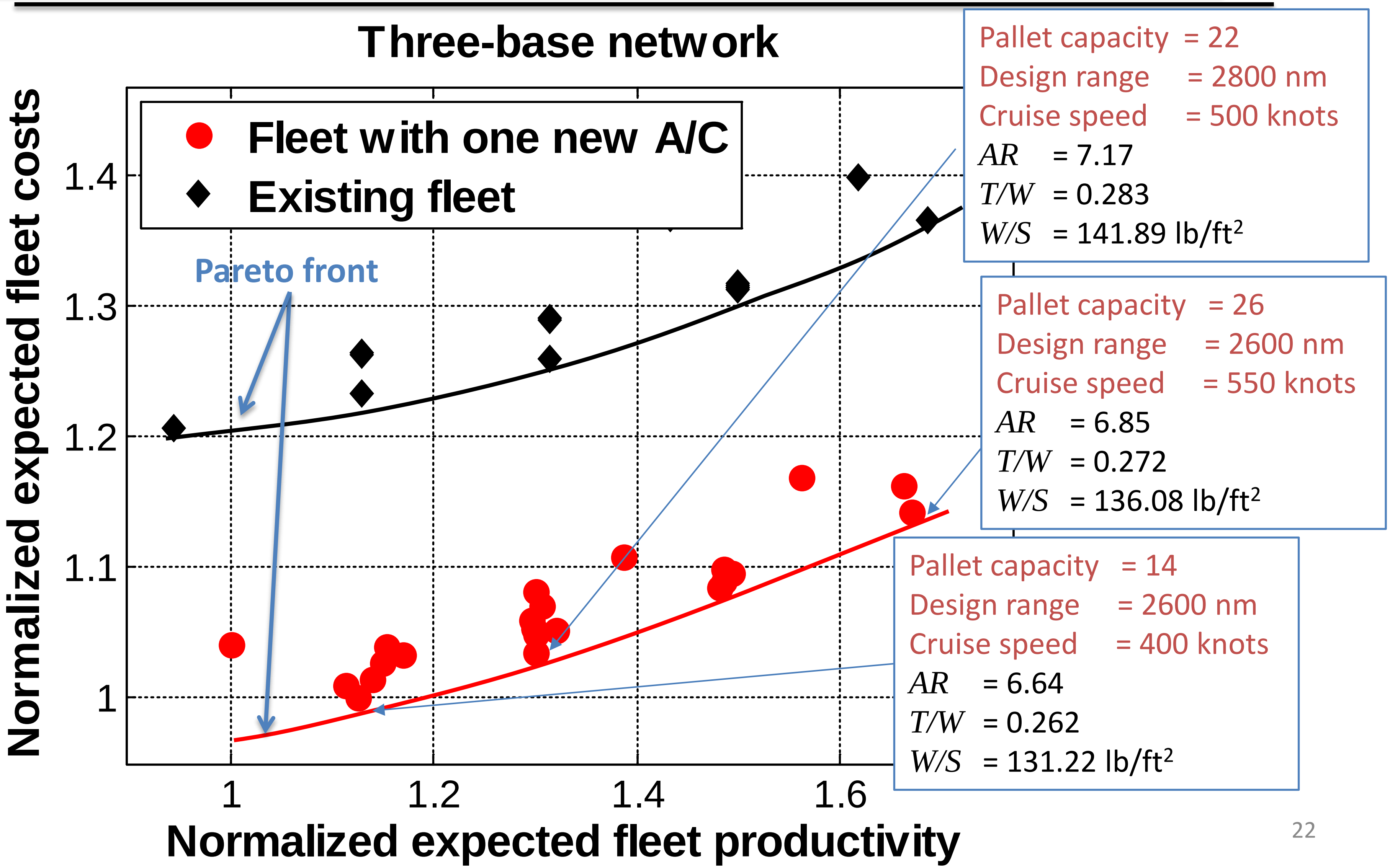
- Simple three-base problem consisting of 6 directional routes
  - Extracted from the GATES dataset
  - Most flown routes in May 2006
- Existing fleet for AMC
  - Three C-5: 36 pallet capacity
  - Three C-17: 18 pallet capacity
  - Three B747-F: 29 pallet capacity
- 1 new aircraft of type X is introduced



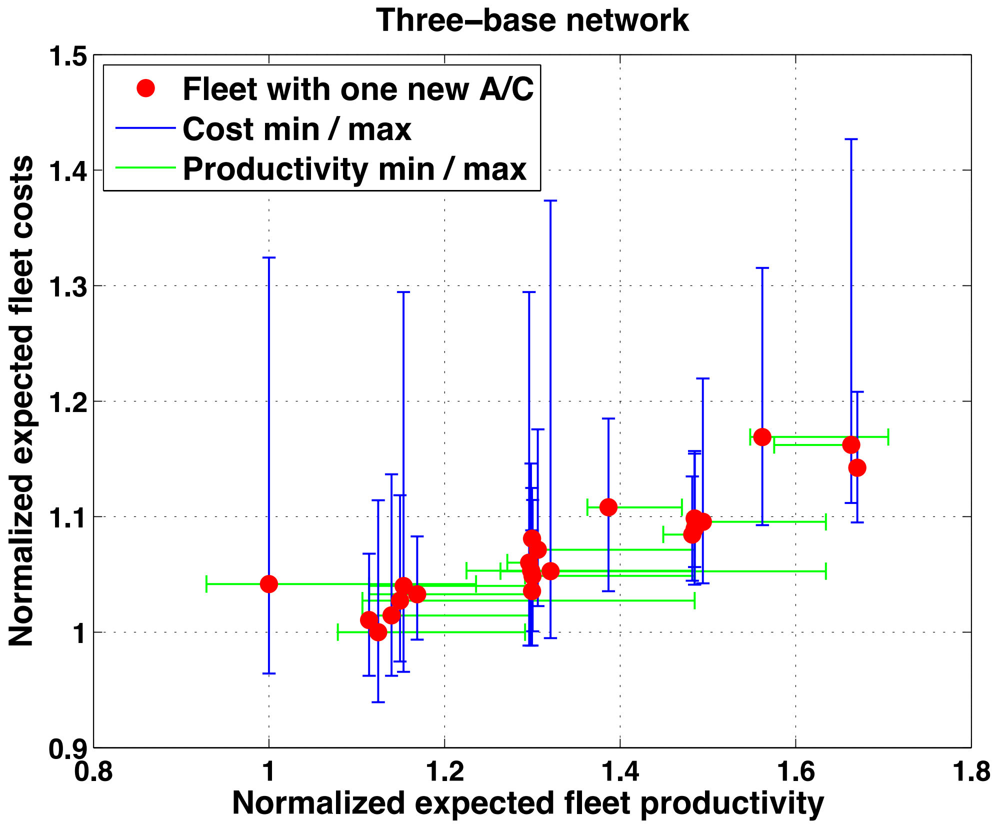
Subspace Decomposition Approach



Three-base Results



Three-base Results



Error bars show min-max variation in fleet-level metrics due to uncertainties in demand and in the new aircraft design

- Degree of dispersion for some results are smaller than for others
- For the same productivity, some maximum fleet costs values on this plot still lower than costs of using existing fleet

CONCLUDING STATEMENTS AND FUTURE WORK

Concluding Statements

- We felt there was a need for an efficient decision-support tool to determine design requirements for new, to-be-acquired systems
- We developed a framework that identifies the tradeoffs between fleet-level metrics
  - Each tradeoff solution describes the design requirements, and optimal design of the new aircraft
  - MCS techniques to address uncertainty in demand
  - DOE to explore uncertainty in system design
  - Framework appears domain agnostic, should apply to many different applications, vehicles, etc.

Future Work

- Robust/Reliability-based problem formulations
- Reduce computational expense
  - Metamodeling or response surfaces
  - Improved sampling techniques

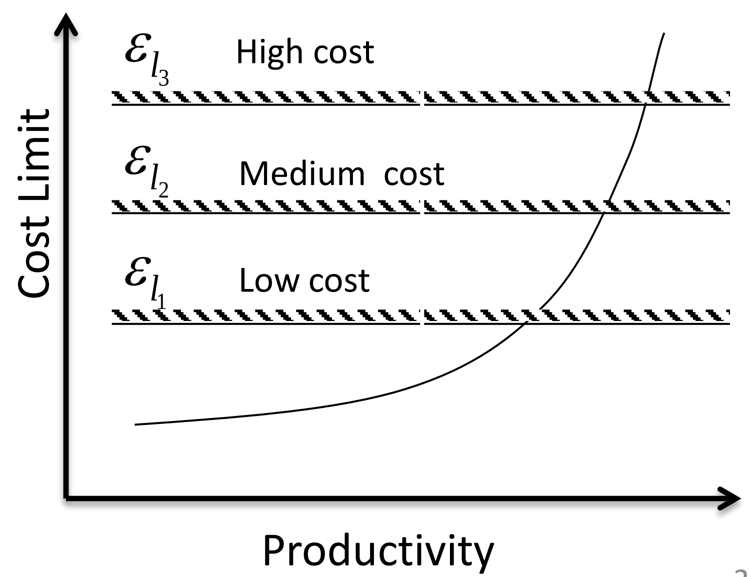
Thank You

BACKUP SLIDES

Multi-Objective Formulation

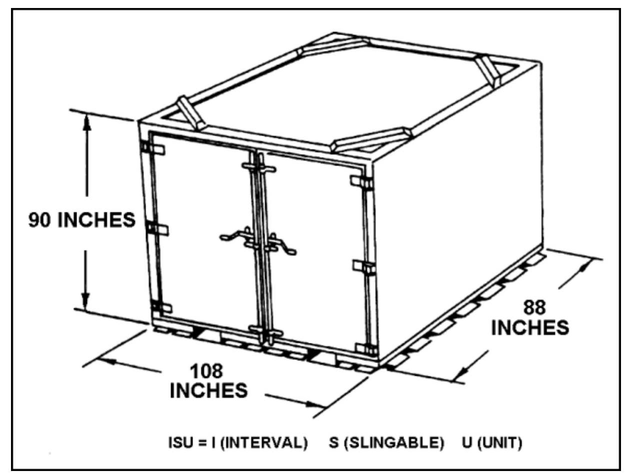
- Two objectives
  - Maximize fleet-level productivity
  - Minimize fleet-level cost
- Epsilon (Gaming) constraint formulation
  - Converts multi-objective to single objective
  - Identify a primary objective
  - Place limits on other objectives (inequality constraints)

$$
\begin{aligned}
&\textit{Maximize} && f_p(x) \\
&\textit{Subject to} && f_l(x) \le \varepsilon_l \qquad l = 1 \ldots n_{obj} \, (l \ne p) \\
& && g_j(x) \le 0 \\
& && h_k(x) = 0
\end{aligned}
$$



Air Mobility Command

- Used Global Air Transportation Execution System (GATES) dataset
- Filtered route network from GATES dataset
  - Demand for subset served by C-5, C-17 and 747-F (~75% of total demand)
  - Fixed density and dimension of pallet (463 L)
- Our aircraft fleet consists of only the C-5, C-17 and 747-F.



Source: *www.amc.af.mil*